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## MULTIPOLE STRENGTH DISTRIBUTION IN $^{156}\text{Gd}$ FROM THE $(p, t)$ REACTION AT $E_p = 40$ MeV

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The  $^{158}\text{Gd}(p, t)^{156}\text{Gd}$  reaction was studied at  $E_p = 40$  MeV with an energy resolution of about 20 keV. One-step DWBA calculations, using a cluster form factor, were used in the analysis to obtain the multipole strength distribution residing in excited states up to 3.37 MeV. A striking feature is the almost complete absence of monopole strength above 2 MeV excitation energy.

$^{156}\text{Gd}$  is a well deformed nucleus in the rare-earth region that is described by the IBA-model in the  $\text{SU}(3)$  limit [1], corresponding to the rotational limit of the collective model of Bohr and Mottelson [2]. Experimentally  $^{156}\text{Gd}$  has been studied extensively during the last few years. A wealth of spectroscopic information on low-lying rotational bands was obtained by Konijn et al. [3]. An inelastic proton scattering experiment [4] on  $^{156}\text{Gd}$  provided qualitative information about the validity of the IBA model by comparison of the obtained experimental hexadecapole transition moments of low-lying  $4^+$  states with theoretical values, calculated in the IBA model framework, but with extending the usual  $s$ - and  $d$ -boson space with a hexadecapole degree of freedom ( $g$ -boson).

In this letter we report on the results of a high-resolution  $^{158}\text{Gd}(p, t)^{156}\text{Gd}$  experiment, which was performed with the initial motivation to investigate (i) the contribution of  $L = 4$  neutron coupled pairs to the ground state of  $^{158}\text{Gd}$  in comparison to the  $S$ - and  $D$ -coupled pairs, and (ii) the distribution of such  $L = 4$  strength in the final nucleus  $^{156}\text{Gd}$ . Not only is the hexadecapole strength observed to reside mainly in states above 2 MeV, in agreement with results from

the  $^{156}\text{Gd}(p, p')$  experiment [4], but also simultaneously new and interesting aspects are observed in the multipole strength distribution of excited states with excitation energy up to 3.4 MeV. Almost all  $0^+$  strength is concentrated in the ground state, while the other multipole strength is much more fragmented and has large fractions in excited states above 2 MeV.

A metallic  $^{158}\text{Gd}$  target enriched to 95.4% was bombarded with a 40 MeV energy analysed beam of protons. The outgoing tritons were detected in the focal plane detection system [5] of the QMG/2 magnetic spectrograph [6] with an overall energy resolution of about 20 keV. Angular distributions were measured from  $6^\circ$  to  $51^\circ$  in steps of  $3^\circ$  with an opening angle of 7.6 msr. In addition a measurement was done at  $0^\circ$ , which was crucial for certain spin assignments. In the  $0^\circ$  run we made use of a Faraday cup mounted inside the first dipole magnet (D1) of the QMG/2 spectrograph. The  $0^\circ$  and  $12^\circ$  spectra are shown in fig. 1.

Angular distributions of transitions to some excited states in  $^{156}\text{Gd}$ , together with DWBA calculations performed with the code DWUCK [7] using a di-neutron cluster form factor with  $2N + L = 10$  ( $N$  is the number of nodes and  $L$  the orbital angular momentum of the form factor) are shown in fig. 2. The optical model parameters used in these calculations for the proton channel were taken from ref. [4]. In a first attempt we used for the triton channel the parameters given in

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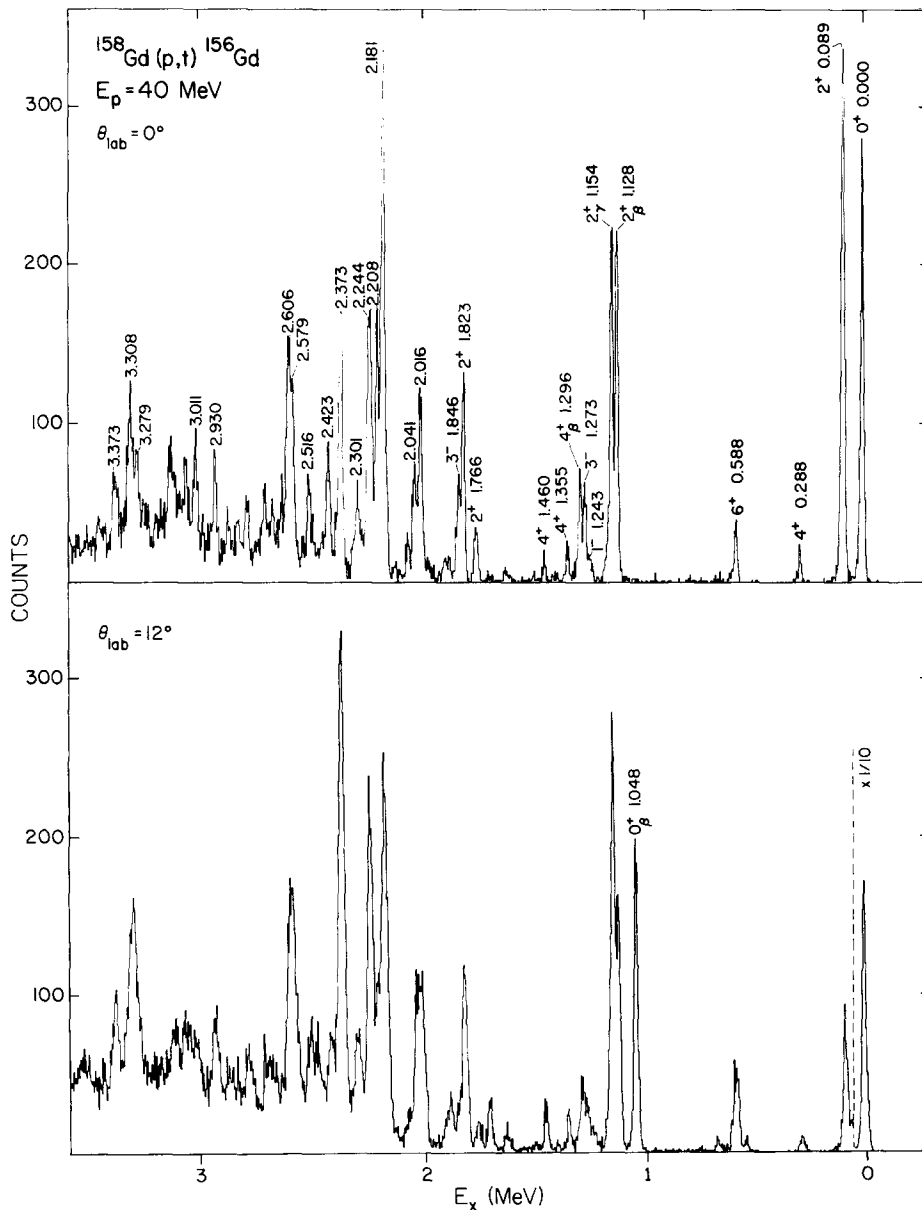


Fig. 1. The  $^{158}\text{Gd}(p, t)^{156}\text{Gd}$  spectra taken at  $E_p = 40$  MeV and  $\theta_{\text{lab}} = 0^\circ$  and  $12^\circ$ . A large number of states is observed especially above 2 MeV. Note the strength of the  $0^+$  ground state, which is quite weak at  $0^\circ$ , but which dominates the  $12^\circ$  spectrum.

ref. [8], which were deduced from an elastic triton scattering experiment at 20 MeV. These gave a reasonable  $L = 2$  fit (dashed curve in fig. 2) to the  $(2^+)$  [9]  $E_x = 2.181$  MeV transition, thus supporting its  $2^+$  assignment. We then further modified successively but slightly the parameters given in ref. [8] such that we

got a best fit to the  $E_x = 2.181$  MeV angular distribution (solid curve in fig. 2). We took this transition as benchmark because of its large cross section and since DWBA fits for transitions to members of the ground state or other low-lying rotational bands were found to be unreliable, due to strong coupled-channels ef-

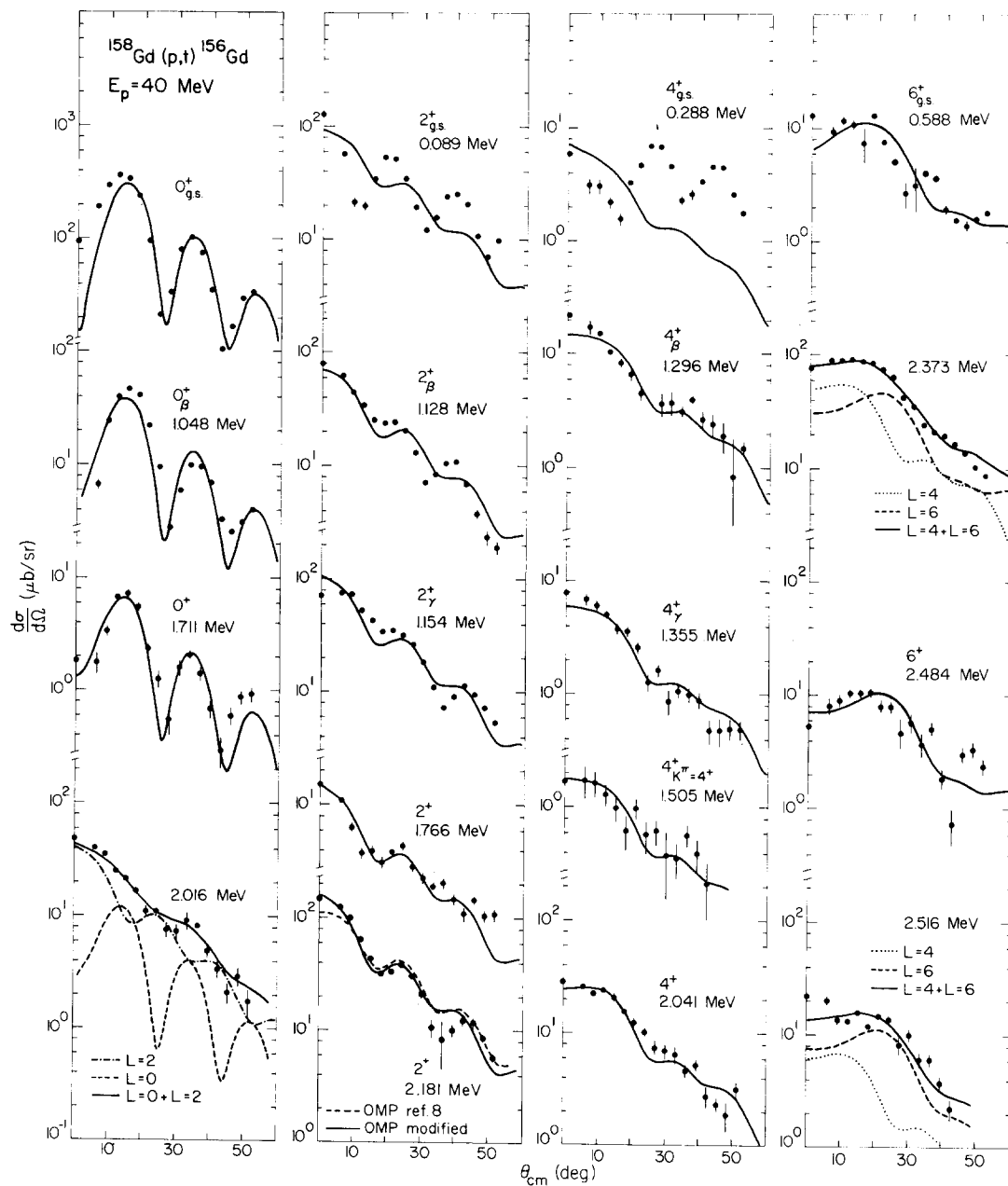


Fig. 2. Angular distributions of some excited states in  $^{156}\text{Gd}$  together with the results of DWBA calculations, using a di-neutron cluster form factor.

fects. The optical parameters are given in table 1.

The DWBA calculations for the  $2^+$  and  $4^+$  members of the gs rotational band are in poor agreement with the experimental angular distributions because of coupled-channels effects. However CCBA calcula-

tions for these transitions with the computer code CHUCK [7], in which inelastic channels were included up to the  $4^+$  state of the gs rotational band in both  $^{156}\text{Gd}$  and  $^{158}\text{Gd}$  and with the same di-neutron cluster form factors as in our DWBA calculations, have

Table 1  
Optical model parameters used in the  $^{158}\text{Gd}(p, t)^{156}\text{Gd}$   
DWBA analysis (potentials in MeV, lengths in fm).

	Proton	Triton	2n cluster
$V$	-48.51	-153	(varied)
$r_f$	1.165	1.14	1.154
$a_f$	0.824	0.768	0.743
$W_v$	-2.97	-17.0	
$W' = 4W_d$	36.04		
$r_l$	1.255	1.485	
$a_l$	0.678	0.87	
$r_c$	1.25	1.25	
$V_{so}$	5.61		
$r_{so}$	1.075		
$a_{so}$	0.816		

not yielded satisfactory fits to the experimental angular distributions. A better description for these angular distributions can be obtained [10] in a coupled-channels scheme using form factors obtained following the formalism described by Ascuitto et al. [10] for the generation of form factors for (p, t) transitions between collective bands in deformed nuclei. Such descriptions are being investigated and will be published elsewhere.

Most of the other experimental angular distributions agree very well with the cluster DWBA calculations (see fig. 2), an observation that seems to support the direct one-step nature of these transitions. Spins and parities could be unambiguously assigned to almost all states up to 3.4 MeV populated in this study by comparison to DWBA calculations. The hexadecapole strength distribution obtained from the present  $^{158}\text{Gd}(p, t)^{156}\text{Gd}$  study is in qualitative agreement with that obtained from the (p, p') experiment [4] in the sense that it is strongly fragmented but with most of the strength above about 2 MeV, as will be discussed below.

To exhibit the systematics in the (p, t) strength distribution we have plotted in fig. 3 the integrated  $0^+$ ,  $2^+$ ,  $4^+$  and  $6^+$  "spectroscopic factors" as a function of excitation energy. "Spectroscopic factors" for states up to 3.4 MeV populated in the present study were obtained by comparison to DWBA calculations. The "spectroscopic factor" for excitation of state  $\alpha$  with spin  $J$  is defined as

$$G_J^\alpha = (2J + 1)(d\sigma/d\Omega)_{\text{exp}} / (d\sigma/d\Omega)_{\text{DWBA}}.$$

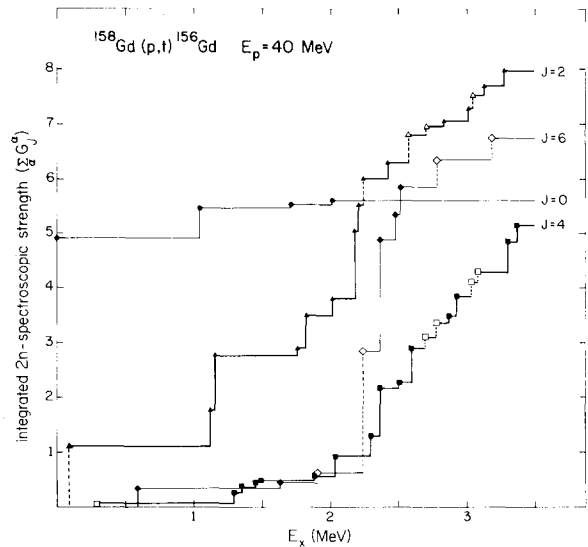


Fig. 3. The integrated "spectroscopic factors"  $G_J^\alpha$  as a function of excitation energy for  $J = 0^+$ ,  $2^+$ ,  $4^+$  and  $6^+$  separately. Dashed lines and/or open symbols denote either doubtful strength (as is the case for the  $2^+$  and  $4^+$  members of the gs rotational band) or doubtful spin assignments (in other cases).

One clear feature is the increase in strength above 2 MeV. This is just above the pairing gap where one expects a large increase in density of states. However a striking feature is the almost complete absence of  $0^+$  strength above 2 MeV. This absence of strong monopole excitation in the region between 2.0 and 3.4 MeV, where so much other multipole strength is located, is very difficult to understand on the basis of normal modes of excitation. If e.g. these  $2^+$ ,  $4^+$  and  $6^+$  states were (fragmented) multipole pairing excitations due to two-neutron removal from deeper shells one would also expect the population of strong  $0^+$  states in the same energy region. Since this is not the case one expects the observed two-neutron pickup strength to be mainly from the valence shells. The present data show a strong collective enhancement only for the  $0^+$  pairing strength that is almost exclusively concentrated in the ground state whereas the other multipoles do not possess this collectivity but instead are spread over many states. This, however, is in conflict with the coherent multipole pairing idea in the framework of the pairing vibrational model [11]. The absence of strongly excited  $0^+$  states could also indicate the existence of bands with  $K^\pi \geq 1^+$  which then may tempt to link

these observed strongly excited states above 2 MeV with the states predicted [12] by IBA-2 to be built up of antisymmetric combinations of  $d_\nu$  and  $d_\pi$  bosons with  $K^\pi = 1^+, 2^+, 3^+$ , etc. However, these antisymmetric states are not expected [12] to be strongly excited in one-step two-neutron pickup processes.

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